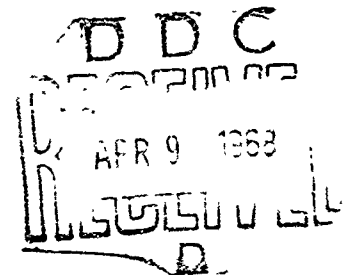


**BRITISH AIRCRAFT CORPORATION (OPERATING) LTD
WEYBRIDGE DIVISION. SURREY. ENGLAND**

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**THE STATE OF THE ART IN DESIGN AND
TESTING CONCEPTS TO ENSURE
STRUCTURAL INTEGRITY**

BY D. JAMES



**FEDERAL AVIATION AGENCY MAINTENANCE
SYMPOSIUM
CONTINUED RELIABILITY OF TRANSPORT-TYPE
AIRCRAFT STRUCTURE**

WASHINGTON, D. C.

NOVEMBER 2nd, 3rd, AND 4th 1966

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British Aircraft Corporation (Operating) Limited
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THE STATE OF THE ART IN DESIGN AND TESTING CONCEPTS
TO ENSURE CONTINUED STRUCTURAL INTEGRITY.

1.0. INTRODUCTION

The topic nominated for discussion in this paper is clearly one of particular interest to those concerned with aircraft maintenance and operation. It has been nominated perhaps as a challenge to those associated with design to indicate that they too recognise the vital importance of continuing structural integrity throughout the economically useful life of the aircraft. The subject is particularly important at the present time because it is highly likely that a stage in development has been reached which will reduce the rate at which aircraft will become obsolete because higher speed types are becoming available, which when due regard is paid to increased passenger appeal, can be operated more economically. The supersonic transport will certainly come for the long range intercontinental and transcontinental routes but the high-subsonic types must continue to bear the brunt of the medium and short range operations. The supersonic types, too, if they are to pay their way must give promise of long life with continued structural integrity if their high development costs are to be justified.

It may be of interest to U.S. readers to conclude this introduction by reference to the report of a British Government Commission investigating the Mechanical Engineering Industry in England. One comment is particularly relevant to the subject being discussed at this symposium. It states that 'The designers responsibility covers the whole process from conception to the issue of detailed instructions for production and his interest continues throughout the designed life of the product in service'. Let it be admitted that there are some engaged in aircraft design as in other fields of design to whom this concept of a designer's responsibility is to say the least unattractive. To them the designer is the man of ideas and ideals, some lesser mortal, call him engineer, technologist, technician or what you will, is the man who has failed to implement the ideas and match the ideals when the product fails to meet its objectives.

2.0. STANDARDS OF STRUCTURAL INTEGRITY

The required standards of structural strength are outlined in the relative Airworthiness Requirements. In some areas they are specific and quantitative whereas in others they are broad and qualitative. In some areas they are rational and soundly based technically and in others they are arbitrary. These differences stem from the fact that they have to take into account an ever-widening background of experience and, at the same time, provide for a continuing advancement into relatively unknown fields. Whatever these standards may be the newly type certificated aircraft will have been subjected to a rigorous investigation to establish that when it does initially enter service, it does meet these standards

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and may reasonably be expected to continue to do so for many years if properly maintained. The keynote then to continued structural integrity is to provide adequate safeguards against deterioration in service. From this point of view it has to be recognised that the airframe is not a static structure but a dynamic structure. Each element is responding to the environment to which it is exposed in such a manner as to be compatible with the constraints imposed on it by adjacent elements. The term environment in this context has to be taken in the widest sense to embrace the external loading conditions, internally induced loads and vibration. The presence of likely contaminants such as fuels, hydraulic fluids, anti-icing fluids and cleaning fluids as well as the normal conception of the atmospheric environment, must be considered. So too must the handling by maintenance personnel!

These environmental conditions can produce a deterioration in the standard of structural integrity by fatigue, stress corrosion, corrosion fatigue, chemical corrosion, hydrogen embrittlement and possibly even creep. These are all terms with which the maintenance engineer will be only too familiar. He will therefore be looking for some evidence that in the design field adequate account has been taken of these and that in the newer types recently come into service he can expect deterioration to be less of a problem than in the past.

3.0. THE IMPACT OF THE ELECTRONIC COMPUTER

There is little doubt that any discussion on the current state of the art in the field of structural design will be expected to make some reference to the impact of the Electronic Computer. Exaggerated claims for the benefits to be obtained from their use have been as widely made as have those for the latest domestic equipment. Some airframe manufacturers have claimed that their product must be more reliable than that of their competitors because the structural analysis has been carried out with the aid of a particular computer programme to which a fancy name has been attached. The facts of the matter are that there are as many systems of structural analysis suitable for the handling of a redundant structure, as there are systems of playing a hand of bridge. Certain factual data are available, analogous to the cards in the player's hand, which have to be studied and played in the light of past experience, with intelligent intuitive assessment deciding the correct sequence of operations. The final result is much more dependent on the experience and intuitive skill of the player than on the particular system which he uses.

The advent of the fast electronic computer has undoubtedly enabled the designer to make better assessments of the strain distributions necessary to ensure deflection compatibility in a complex structure exposed in a particular load environment. From this point of view therefore a more reliable structure should be produced. Fatigue and stress corrosion failures resulting from unexpectedly high local strain concentrations should not be experienced if the data fed into the computer has been correctly assessed and the data produced by the computer correctly applied. However, a question perhaps still to be resolved is

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whether there is danger of the progressive fall away in the art of engineering judgment, which is inherent in the increasing dependence on computers, producing a situation in which the maintenance engineer finding a defect in service will no longer be able to get advice as to how to deal with it until a new programme has been written and a new analysis made. This possibility is one which at this stage may be somewhat exaggerated but, nevertheless, with the increasing tendency to specialisation within the field of structural design, it is one against which those responsible for the design of structures must make adequate safeguards.

With these warnings against excessive optimism being placed on the improvements in structural integrity arising directly from the fact that much of the work is done with the aid of electronic computers it is sufficient to say in the context of this paper that the computational capability provided does enable the designer to complete a more detailed analysis, in an acceptable time scale, than would be possible otherwise. There is therefore less reliance on engineering judgment or perhaps better expressed a sounder background against which to use engineering judgment.

Reference has been made earlier to the fact that the airframe is a dynamic structure responding to its environment. In considering the loading environment the airworthiness requirements specify this in terms which are generally applicable to the concept of a rigid structure. However it is required that the effects of flexibility shall be taken into account if these can significantly affect the load distribution arising from the specified 'mean' load condition. It is also recognised that superimposed on these 'mean' conditions there can be continuously varying loads due for example to turbulence in flight, unevenness of runways under ground loading conditions as well as due to pilot action. The various structural components are therefore continuously in motion around some average deflected position. The frequencies and amplitudes of the motion depend on the natural frequencies of the various components, the interaction between the components, and the magnitude and frequency of the disturbing forces which may be completely random. The electronic computer has vastly improved the capability for analysing these dynamic conditions and in consequence for more correct assessment of the stresses arising therefrom.

4.0. THE EXTERNAL LOADING ENVIRONMENT

4.1. Turbulence

A major factor affecting the integrity of the aircraft structure is clearly the flight loading environment which is much affected by turbulence. This has perhaps been much more forcibly demonstrated in the military aircraft field than in the civil aircraft field. Aircraft designed primarily for long high altitude patrol-type operations have switched to very low altitude-type operations with the result that the impact of the changed environment has been dramatically emphasised. The initial advent of the

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jets in the civil aircraft field with consequent continued operation at high altitude was approached with some caution by the Airworthiness Authorities. The expectation that exposure to turbulence would be reduced by the ability to adopt storm avoidance procedures was tempered by the knowledge that the jets would be operating more closely to their design limits and by virtue of their greater aerodynamic cleanliness would require a much greater distance in which to slow down. The phenomenon of clear air turbulence was also giving cause for concern. Comprehensive investigations by N.A.S.A. and by the R.A.E. in England have produced a much better knowledge of the general levels of turbulence which can be expected by an analysis of much V.G.H. recorder-type data. The availability of the Flight Recorders of various types which are now required to be fitted to all jet aircraft primarily as an aid to accident investigation has provided further opportunity for improving our understanding of the typical operational environment. In England all recorder tapes are subjected to a superficial examination and any records which show evidence of some non-routine condition are subjected to a critical analysis and an explanation sought for them. When appropriate pilots may be interviewed and meteorological data examined. Data obtained from sources such as this will provide the basis against which the airworthiness authorities can keep their requirements under review.

4.2. Vibration

It is considered appropriate to make some special reference to the significance of vibration as a source of fatigue troubles. The old piston-engined types carried a burden, in the form of an essentially unbalanced combustion system and a large whirling propeller, which was a vibration producer second to none. The optimists predicted the disappearance of engine-induced vibration as a producer of random fatigue failures with the advent of the turbine engine. Also they overlooked the need for the thrust reverser to make good the loss of propeller drag and the fact that, with the development of higher powered engines with ever increasing tail pipe pressure ratios, the comforting note of power produced by the jet efflux was a potential contributor to the problems of the structural designers and maintenance engineers.

4.3. Landing Gear Loads

No discussion on the load environment as affecting the structural integrity of an aircraft would be complete without some reference to the landing gear and the forces to which it is subjected and which it transmits to the structure as a whole. Few people realise that the average civil transport aircraft travels more miles per annum on the ground than the average motor car does. The ground running loads are therefore of considerable importance. They are subject to greater variation than are the flight loads. The surface over which the aircraft runs will vary from aerodrome to aerodrome, pilot handling of the aircraft, particularly the approach to turns and the use of brakes and differential thrust, all play their part in making landing gear loads somewhat unpredictable. Couple this with the fact they often are carrying unevenly worn and

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unbalanced tyres which, rotating at high speed, are a powerful source of vibration and all is set for a component which will always keep the maintenance man on the alert.

5.0. THE MINIMISATION OF DETERIORATION IN SERVICE

An outline has been given of some of the factors influencing deterioration in service over which the structural designer per se has little influence, notably the external loading environment. It is appropriate now to consider the trends in design which are aimed at minimising the deterioration hazard.

5.1. Fatigue

The most important factors contributing to the elimination of fatigue failures are a correct assessment of the load environment, choice of material and working stress level. From the load environment point of view there is a vast difference between that experienced by the inter-continental jet cruising at say 35,000 feet with a 6-7 hour flight time and that experienced by the local service jet with perhaps a flight time of 30 minutes. The significance of this differing environment must be considered. No apology is made for the presentation of the data in Fig.1. This is compiled from a well-known U.S. publication viz. Mil. Handbook No.5. Fig.2. compiled from the same data shows that for a typical aircraft wing tension structure the longer fatigue life potentially available by the use of the 2024 T4 material as compared with a corresponding design in 7075 T6.

British Aircraft Corporation policy for upwards of 12 years has been to restrict the use of the 7000 series alloys to selected applications partly because of this poor fatigue performance. In the case of the BAC One-Eleven these alloys are not used at all.

The curves shown illustrate that the development of high static strength in an alloy is not necessarily indicative of a corresponding increase in fatigue performance. The same is true in the case of the steels and again with steel components it is necessary to carefully consider the particular application before making the choice of material. On the BAC One-Eleven no steel is used at a higher Heat Treatment level than 180,000 p.s.i. nominal. The reason for this decision which is not solely based on fatigue grounds, will be discussed later.

Fail-safe design philosophies have been the subject of much discussion over the years. However a fail-safe design in which too much emphasis has been placed on the fail-safe aspects and not enough on the achievement of a reliable basic fatigue life is not a sound approach. It introduces a system whereby too much responsibility is placed on the line maintenance engineer. B.A.C. philosophy is to design for an adequate basic fatigue life but at the same time use fail-safe concepts wherever possible. The acceptance of a structure relying for its integrity on the fail-safe concept must depend on an assessment of the strength of

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the cracked structure and an assessment of the rate at which a crack will propagate in it. Both of these quantities are, like the basic fatigue endurance, material and stress level dependent. Again the balance of evidence is in favour of the 2000 series alloy in preference to the 700 series.

5.2. Stress Corrosion

A cause of reduction of structural integrity which follows very closely behind fatigue has been the stress corrosion of aluminium alloys. Stress corrosion failures require the presence of a sustained stress in a corrosive environment. It must be accepted in this context that all environments are corrosive and therefore that a sustained stress always means a stress corrosion hazard. It must also be accepted that it is not possible to design and build a structure to such closely controlled dimensions as to eliminate all assembly stresses and therefore the risk of a stress corrosion failure must exist unless a high standard of corrosion protection is provided and steps are taken in design to ensure that the grain direction in the component is orientated in the most favourable direction.

It is encouraging to record that material manufacturers have recognised the existence of the problem as a material problem and the developments are taking place which give promise for the future. British Aircraft Corporation are actively participating in trials of these developments as will be seen from Fig.3.

5.3. Corrosion and Corrosion Protection Methods

British Aircraft Corporation approach to corrosion is to recognise that the corrosive environment is always present and to take this into consideration in selecting materials. For this reason the use of magnesium alloys for structural purposes is prohibited. These alloys are only permitted in applications such as readily replaced free standing components in control systems where maintenance inspections and lubrication procedures will ensure that evidence of corrosion is easily seen. Where it is used best cleaning and protective systems are employed.

On corrosion protection generally it is the policy to apply two coats of a specially developed epoxy primer paint to all detail parts before assembly and wherever possible to apply the finishing coat at this stage too. This ensures that the paint is applied when the detail parts are in a freshly cleaned condition. The accelerated drying treatment is carried out immediately afterwards. The result is an extremely durable and tough protective treatment.

In the development of this paint the ability of the paint film to match under fatigue test conditions the endurance of the metal components to which it was applied, was one of the qualifying tests. Many formulations were rejected because of deficiencies in this respect.

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5.4. Hydrogen Embrittlement in Steel Components

The use of the high strength steels brings with it a hazard which is perhaps analogous to the stress corrosion hazard with the aluminium alloys viz Hydrogen Embrittlement failures. In some cases breakdown of the protective treatment system has produced local areas in which corrosion occurs. Hydrogen is produced in this process which perhaps in combination with an already high level of residual hydrogen in the basic steel is sufficient to cause a hydrogen embrittlement failure.

Undoubtedly the best protective treatment for any steel component is cadmium plating followed by the application of a paint such as that referred to in the previous section. Unfortunately the electroplating processes introduce hydrogen into the steels and this has to be removed by subsequent baking treatments. The sustained high temperatures necessary for this present a problem with the high strength steels. Practice in this direction varies considerably, in Sweden for example the cadmium plating of steels at strength levels higher than 130 K.S.I. is discouraged if not actually forbidden. In the U.K. its use at strength levels higher than 200 K.S.I. is discouraged.

The British Aircraft Corporation view is that any steel which brings with it the hazard of an hydrogen embrittlement failure if a small area of protective treatment gets damaged is not right for civil aircraft business and it restricts its strengths to 200 K.S.I. nominal maximum. In the case of BAC One-Eleven 180 K.S.I. maximum is used.

6.0. TESTING METHODS

6.1. Fatigue

There is wide acceptance of the view that a substantial amount of fatigue testing is necessary in order to provide a sound basis for the substantiation of continued structural integrity. The real problem in this field is the degree to which the testing effort should be spread over the testing of the complete airframe or major components and the testing of selected subcomponents. The case for the testing of complete components and in some cases of the complete airframe is that such tests ensure that internally induced stresses are correctly represented and that errors in the assessment of stress distributions in the redundant structure are also covered. Against testing of the complete airframe or major component is the high cost and the fact that there is inevitably a considerable time lag. Subcomponent testing can be carried out more expeditiously uncomplicated by the fact that the most damaging flight conditions for one component are not necessarily the critical ones for other components.

B.A.C. policy in this area is to combine the two approaches.

Fatigue testing is carried out throughout the whole range from the small coupon type specimens representative of sample joints, through the larger specimens representative of typical major structural discontinuities,

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such as fuel tank access panels, to components building up to the major airframe assemblies, although these are not necessarily integrated into one specimen. In the case of the B.A.C. One-Eleven wings, fuselage, horizontal and vertical stabilizers and landing gear are all covered in this way. In all cases from the simple specimens upwards loading programmes are assessed to give the best possible load spectrum representative of the typical operational cycle experienced by the particular component under average forecast operational conditions.

Fatigue testing facilities employed include standard machines, with capacities ranging from 450,000 lb. downwards, equipped for automatic operation with a preset programming facility on which the selected load spectrum is set. These are supplemented by ad hoc facilities designed for particular components again equipped for automatic programme control. For the major components special loading frames and loading gear are employed. The achieved testing rate on the B.A.C. One-Eleven major facility is up to 1000 flights per week.

It is recognised that on this type of testing vibration effects are missing. In order to cover the effects of vibration due to the use of reverse thrust on the stabilizers these are periodically subjected to a forced vibration in which an electromagnetic exciter is used to reproduce the amplitudes and frequencies as experienced on the aircraft as determined experimentally on the aircraft.

Some fatigue facilities are available for the study of these effects. Fig.4. shows a representative B.A.C. One-Eleven horizontal stabilizer specimen in this facility.

CONCLUSION

A brief presentation of the British Aircraft Corporation approach to the problems of maintaining a high standard of structural integrity has been presented. The discussion has been restricted to those topics which it is thought will be of interest to those responsible for aircraft maintenance.

ACKNOWLEDGMENT

The author appreciates the opportunity which has been given him to present this paper in the U.S.A. and thanks the British Aircraft Corporation for permitting him to do so.

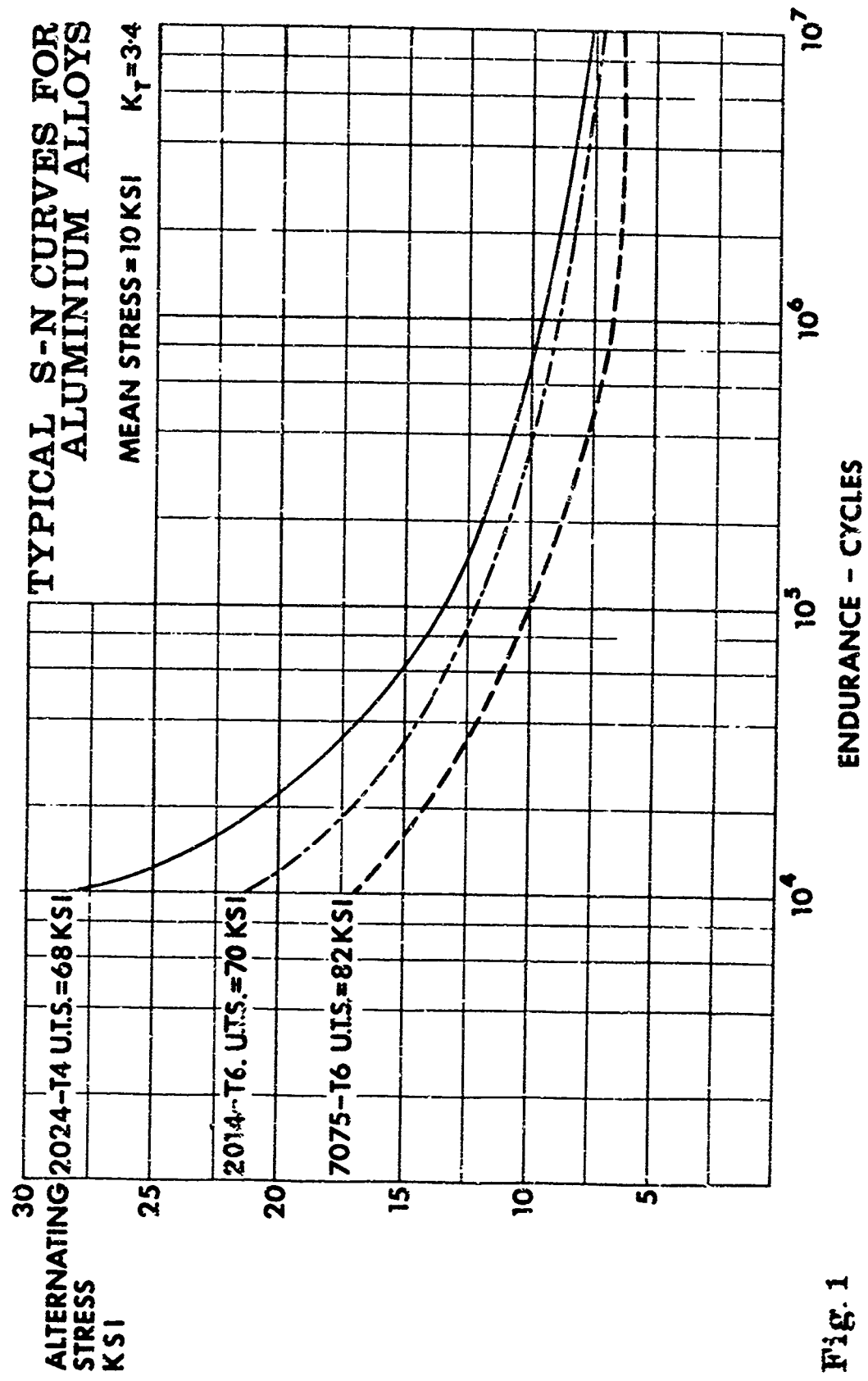


Fig. 1

REQUIRED LIFE v FACTOR OF SAFETY FOR AL. ALLOYS

Fig. 2

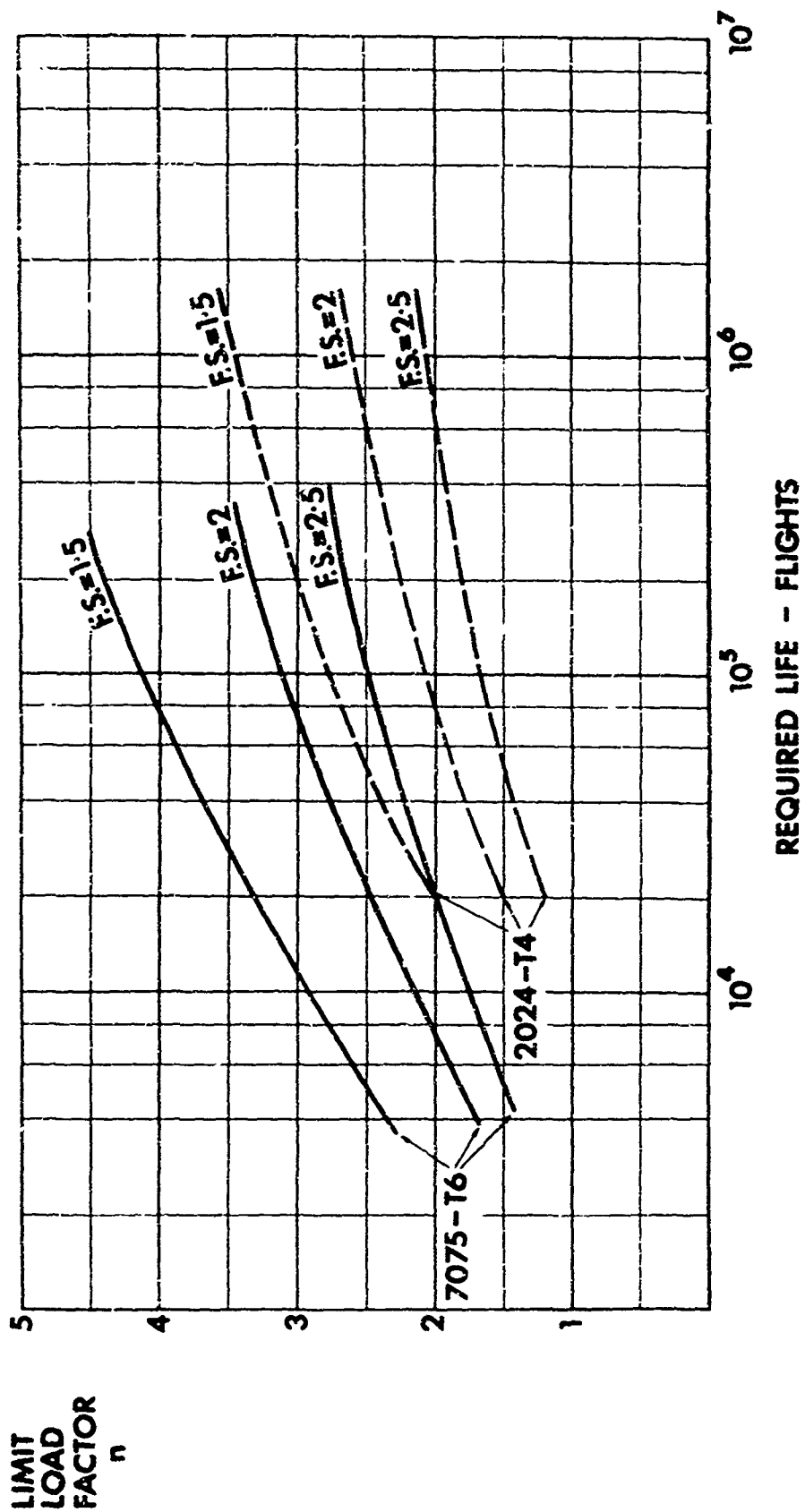
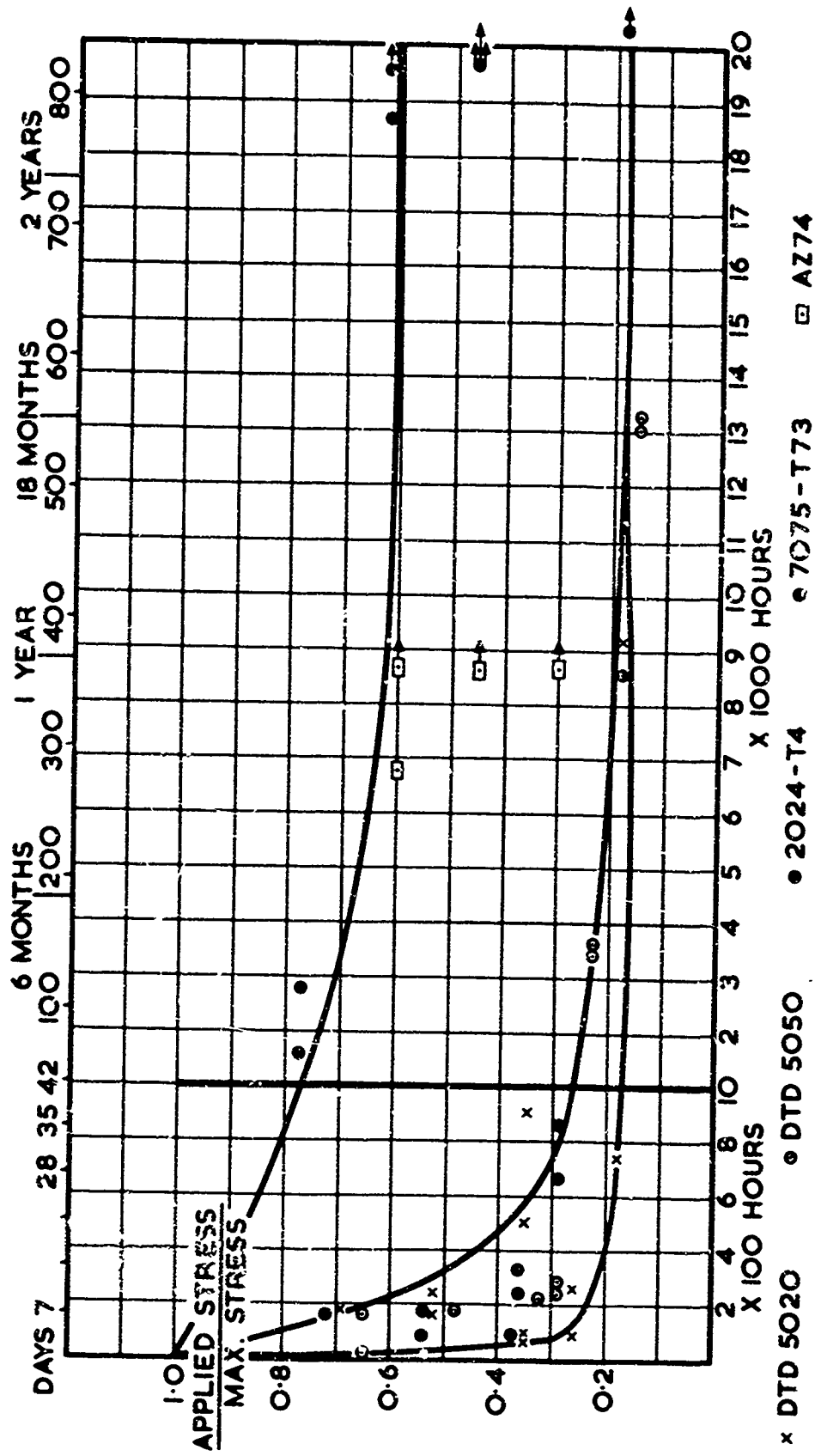


FIG. 3 STRESS CORROSION TESTS ON ALUMINIUM ALLOYS
EXPOSED TO AN INDUSTRIAL ATMOSPHERE



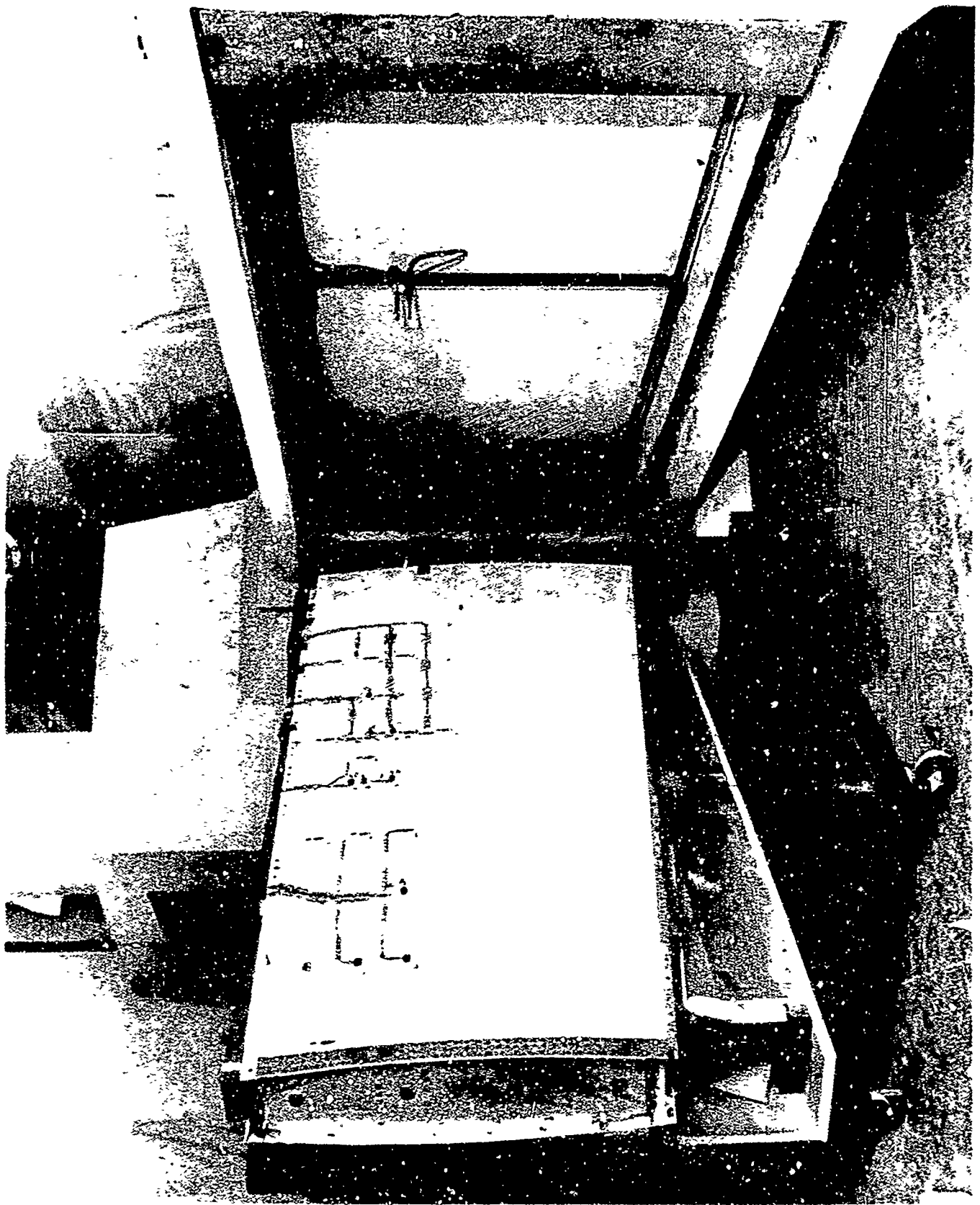


Figure 4. Sonic Fatigue Test Facility.